submitted to *Pubs. Astron. Soc. Pac.* 2002 August 31

A meta-analysis of cosmic star-formation history

David W. Hogg

Center for Cosmology and Particle Physics, Department of Physics, New York University, 4 Washington Place, New York, NY 10003
david.hogg@nyu.edu

ABSTRACT

A meta-analysis is performed of the literature on evolution in cosmic star-formation rate density from redshift unity to the present day. The measurements are extremely diverse, including radio, infrared, and ultraviolet broad-band photometric indicators, and visible and near-ultraviolet line-emission indicators. Although there is large scatter among indicators at any given redshift, virtually all studies find a significant decrease from redshift unity to the present day. This is the most heterogeneously confirmed result in the study of galaxy evolution. When comoving star-formation rate density is treated as being proportional to $(1+z)^{\beta}$, the meta-analysis gives a best-fit exponent and conservative confidence interval of $\beta = 2.7 \pm 0.7$ in a world model with $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$ and $\beta = 3.3 \pm 0.8$ in $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$. In either case these evolutionary trends are strong enough that the bulk of the stellar mass at the present day ought to be in old (> 6 Gyr) populations.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: stellar content — history and philosophy of astronomy — methods: statistical — stars: formation

1. Introduction

The study of galaxy evolution is filled with negative results. Despite intensive efforts, only small or subtle evolution has been detected in the number density of field galaxies (eg, Lilly et al. 1995; Heyl et al. 1997; Hogg 1998; Lin et al. 1999; Cohen 2002), in their masses (eg, Vogt et al. 1996, 1997; Treu et al. 1999; Brinchmann & Ellis 2000; Cohen 2002), or in their clustering relative to “stable clustering” (eg, Le Févre et al. 1996; Carlberg et al. 1997; Small et al. 1999; Hogg et al. 2000; Carlberg et al. 2000), from redshift unity to the present day. At the same time, the constraints on galaxy evolution have not been made strong enough to allow definitive results from the classical cosmological tests. Has the galaxy evolution community got anything positive to say? Indeed it has.

For a long time it has been observed that apparently faint and (at one time presumed to be, now largely known to be) distant galaxies are, on average, bluer in color than their local counterparts (eg, Koo & Kron 1992, and references therein). This was attributed to higher star-formation rates or younger ages at earlier times. As the data on distant galaxies has improved, this conclusion has been bolstered, with photometric and spectroscopic observations spanning the full electromagnetic spectrum.

Often, the literature on galaxy evolution focuses on disagreements between star-formation rate measurements, as it should, since such disagreements ought to point to important issues in selection effects, dust extinction, the initial mass function of stars, and stellar population syntheses (eg, Cowie et al. 1999; Bell & Kennicutt 2001; Hopkins et al. 2001; Sullivan et al. 2001). What is much more remarkable than the disagreements between the measurements, however, is the very important respect in which virtually all studies of galaxy star-formation rates agree: The star-formation rate density in normal galaxies has been declining from redshift unity towards the present day.

It is of great importance that the star-formation measurements span a number of different observational techniques, a number of different regions in the electromagnetic spectrum, and a number of physically different star-formation indicators. The different studies suffer from different selection effects and have different sensitivities to dust extinction and the stellar initial mass function. For example, as the absorption due to dust in a star-forming galaxy increases, the ultraviolet luminosity decreases, the optical Hα line decreases by less, the radio emission from supernovae is unaffected, and the far-infrared emission actually increases. The different measurements are also performed by different groups of investigators, with different approaches and different preconceptions. This heterogeneity of the confirming evidence makes the decline in star-formation rate density the most secure result in galaxy evolution, and one of the most secure in all of astrophysics.

In what follows, a quantitative meta-analysis of the star-formation history literature is performed, in which the declines inferred from different observational studies are compared in a fair way, to establish the consistency of the literature and combine the measurements responsibly. Because of the "responsibility" constraint, many studies relevant to questions of star-formation rate have been dropped from the meta-analysis; even though almost all of them support the final conclusions.

The star-formation rate measurements in question are measurements of mean comoving cosmic star formation rate density $\dot{\rho}_*$, the average mass in stars formed per unit time per unit comoving volume. As discussed below, except where specifically noted, all reported measurements are corrected to a cosmological world model with $(h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7)$, where $H_0 = 100\,h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ and Ω_M and Ω_Λ are the present-day, scaled densities of matter and cosmological constant (eg, Hogg 1999).

2. Star formation indicators

As emphasized above, confidence in the result that star formation is evolving comes from from the heterogeneity of star formation indicators that show similar evolution.

2.1. Rest-frame ultraviolet continuum

Short-lived stars tend to have high temperatures, so the ultraviolet continuum of galaxies is an indicator of recent star formation. With optical telescopes, near-ultraviolet wavelengths $\lambda \sim 2500$ Å can be observed in the U (or similar) bandpass at redshifts $z > 0.4$. A stellar population created in a short burst is bright at 2500 Å for ~ 20 Myr (eg, Bruzual A. & Charlot 1993; Leitherer & Heckman 1995) because only short-lived stars emit at these wavelengths.

The near-ultraviolet luminosity of a galaxy is a direct measure of its young stellar population, and therefore a good indicator of recent star formation activity. The primary disadvantage of this indicator is that it is strongly affected by dust extinction; correction for extinction requires good knowledge of the reddening law in the near-ultraviolet and the geometry of the dust relative to the stars (eg, Calzetti et al. 1994). Another disadvantage is that ultraviolet continuum can be produced by nuclear activity; in fact possible contamination by nuclear activity is a disadvantage of all of the indicators.

At redshifts $z < 0.4$, the 2500 Å emission can only be estimated from the ground by extrapolation from the visual and near-ultraviolet. This is a disadvantage, because the extrapolation depends on the shape of the galaxy spectral energy distribution in the ultraviolet; this is very sensitive to small amounts of dust or small changes in star formation history and activity. The forthcoming GALEX mission (Martin et al. 1997), which will obtain ultraviolet imaging of normal nearby galaxies, will solve this problem.

2.2. Hα emission line

The Hα line is emitted in the recombination spectrum of hydrogen; it is a star formation indicator because only short-lived stars produce significant luminosity in photons with energies above the hydrogen ionization energy 13.6 eV.

Because it involves ionization and recombination, the Hα line is in some sense a less-direct indicator of recent star formation. However, it is weighted towards even higher-mass (and therefore shorter-lived) stars. It is also less affected by dust extinction (though not completely insensitive). The indicator has the disadvantage that in a significant fraction of galaxies, the total Hα luminosity can be dominated by an active nucleus.

At redshifts near unity, Hα can only be measured with near-infrared spectrographs. Some such

instruments are now on-line, but measurements of line strengths in faint galaxies have not been made in large numbers. This is likely to change in the near future.

2.3. Near-ultraviolet emission lines

Ultraviolet radiation from stars ionizes many atomic species, not just hydrogen, and several of these species emit bright lines in the optical and near-ultraviolet in their recombination spectra. The most prominent and useful line is the forbidden [O II] line at 3727 Å, because it is bright and visible in optical spectrographs in a wide redshift range $0.2 < z < 1.3$. Because the line is forbidden, it is a collisionally excited transition emitted by Oxygen in ionization regions with electron densities $n \sim 10^4$ cm^{-3}. These conditions are common around very young and forming stars.

In the local Universe, [O II] emission appears to be closely related to Hα emission (Kennicutt 1992), so it is a reasonable tracer of star formation. However, its strength depends on the metallicity, density, and dust content of the nebular gas, so the relationship between line luminosity and star formation rate is expected to have a much greater variance than that for the Hα line. Its primary advantage is in redshift coverage.

The [O II] line shares the disadvantage that it can be contaminated by nuclear activity.

2.4. Far-infrared continuum

Star forming regions are often very dusty; thick dust surrounding young stars will absorb ultraviolet and optical emission and re-emit it at far-infrared wavelengths $30 < \lambda < 200$ μm. Since short-lived stars are far more luminous than long-lived stars (by a factor which overwhelms their relative scarcity in typical initial mass functions), the far-infrared luminosity of a galaxy may be approximately the bolometric luminosity of its dust-enshrouded, short-lived stars. This makes it a star-formation indicator.

Far-infrared emission is a less direct indicator than ultraviolet flux, but it has opposite sensitivity to dust; dustier galaxies are better measured, while pristine galaxies are missed. It has the enormous disadvantage that the far infrared cannot be measured directly at ground-based telescopes. It must be inferred from sub-millimeter and near-infrared measurements. The study of far-infrared emission will be revolutionized with the SIRTF mission. There is an additional problem that the far-infrared emission can have a substantial contribution from an active nucleus, and the visual extinction makes it difficult to differentiate sources of luminosity (eg Sanders & Mirabel 1996, and references therein).

2.5. Radio continuum

A short time ~ 30 Myr after a burst of star formation, stars with masses $M > 8\,M_{\odot}$ complete most of their nuclear burning and explode in what are expected to be Type II and Type Ib supernovae, although the evidence for this association is not iron-clad (eg, Filippenko 1997, and references therein). These supernovae and their remnants are bright at radio frequencies $1 < \nu < 100$ GHz for $t \sim 100$ Myr (eg, Condon 1992, and references therein).

Radio observations have the great advantage that they are insensitive to dust. Star formation measurement is not rocket science, but the radio indicator is the least well-calibrated, simply because the energetics of radio supernovae are less well-understood than other aspects of stellar populations. Like the other indicators, radio measurements can be contaminated by active nuclei, which, at faint levels, are not easily distinguished from supernovae.

2.6. Other methods

Many other methods have been suggested but wait for new data. It has been suggested that the X-ray sources created by stellar evolution could be used as an indicator (Ghosh & White 2001). Much work is going into understanding the winds from forming and young stellar populations (eg, Kudritzki & Puls 2000, and references therein); one can imagine measuring star formation rates using mechanical, rather than electromagnetic, luminosity. When the SIRTF mission is able to calibrate the relationships between strong mid-infrared spectral features from interstellar molecules and the ultraviolet radiation fields that excite the transitions (eg, Li & Draine 2002), there will be a new industry of understanding star formation activity via the mid-infrared.

3. Method and results

3.1. Studies excluded

This meta-analysis is of star-formation rate variation *within* a single observational study, at redshifts $z < 1$. For this reason, no study was included in this meta-analysis if it did not report more than one independent $z \leq 1$ star-formation rate measurement. This excluded several otherwise relevant studies (eg, Connolly et al. 1997; Madau et al. 1998; Treyer et al. 1998; Yan et al. 1999; Sullivan et al. 2000; Thompson et al. 2001). An exception was made for a group of very similar surveys for Hα line luminosity density, which were put together to make a “combined Hα” study, described below.

Several relevant studies were dropped because the targets were selected or the results were presented such that the results could not be fairly used as cosmic star-formation rate measurements (eg, Schade et al. 1996; Cowie et al. 1997; Guzman et al. 1997; Lilly et al. 1998; Blain et al. 1999),

or because estimates of measurement uncertainties were not provided (eg, Cram 1998).

Only publications appearing in the refereed literature prior to 2002 August 1 were considered.

3.2. Studies included

The cuts left ten studies (Lilly et al. 1996; Hammer et al. 1997; Rowan-Robinson et al. 1997; Hogg et al. 1998; Cowie et al. 1999; Flores et al. 1999; Mobasher et al. 1999; Haarsma et al. 2000; Jones & Bland-Hawthorn 2001). Notes on individual studies are given in Table 1, but in most cases, the confidence interval on each star-formation-rate-density $\dot{\rho}_*$ point was measured (with a ruler) from the relevant Figure in each paper. The measured points are shown in Figure 1. At any redshift, there is a large scatter.

In addition to the primary ten studies, three very similar studies of the cosmic Hα line luminosity density (Gallego et al. 1995; Tresse & Maddox 1998; Glazebrook et al. 1999), each measuring the density at a different redshift, were combined into a single "combined Hα" study, which was included as if it were an additional individual study.

3.3. Data fitting

Each data point, centered on some redshift z, was crudely "corrected" to the default world model used in this paper by the correction factor

$$f = \left(\frac{D_L^2}{\mathrm{d}V_C/\mathrm{d}z}\right)^{-1} \left(\frac{\widetilde{D}_L^2}{\mathrm{d}\widetilde{V}_C/\mathrm{d}z}\right) \tag{1}$$

where D_L and V_C are the luminosity distance and comoving volume (eg Hogg 1999) out to z in the cosmological world model employed in the study in question, and $\widetilde{D}_L$ and $\widetilde{V}_C$ are the same but for the fiducial world model $(h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7)$ used here. This world-model correction makes two assumptions: The first is that the star-formation indicators have been calibrated somehow independently of Hubble constant, in the sense that a change in the Hubble constant changes the inferred luminosity and inferred star formation rate by the same factor. The second is that each reported data point can be treated as well-localized at its redshift; for the precisions reported in these studies this ought to be fine.

Linear fitting to the model $\dot{\rho}_* \propto (1+z)^\beta$ was performed in $\log(\dot{\rho}_*)$ space with points weighted according to their reported uncertainties. By this procedure, the confidence intervals reported in the individual studies are treated as representing Gaussian uncertainties in $\log(\dot{\rho}_*)$ space. In detail, of course, this assumption is incorrect, but since none of the studies is extremely precise and since most of the reported uncertainties are not accurate (most only include the Poisson contribution), the assumption does not significantly affect the results. The best-fit β values and the linear-fitting uncertainties provided by the covariance matrix are given in Table 1 and shown in Figure 2.

3.4. Results

The weighted mean (using the inverse variances from the linear fits as weights) of the best-fit β values is $\beta = 2.74 \pm 0.28$, a nominal ten-sigma result.

All but two of the β measurements are consistent (at $\sim 2\,\sigma$) with the weighted mean. In detail, the weighted mean relies on the assumption that the studies have reported accurate uncertainties; but weighted and unweighted mean values barely differ. Of the two outliers, one (Hammer et al. 1997) appears to be an outlier simply because it carries such a small uncertainty; most of the studies report only Poisson contributions to their error budgets, so the uncertainties are better treated as lower limits. The other outlier (Mobasher et al. 1999) is more problematic, but the sample is small (only 23 galaxies in the $z \sim 0.5$ point), the sample is cut on both radio power and optical magnitude (at a fairly bright $R < 21.5$ mag), and sources spectrally classified as having active nuclei were excluded (roughly 25 percent of the sample).

Given the underestimated measurement uncertainties, a much more conservative method for computing a mean with a reasonable confidence interval is the bootstrap resampling technique. In each of 10^4 trials, ten studies were randomly chosen (with replacement) from the group of ten and a weighted mean (using inverse variances from the linear fits as weights) for β was computed. Note that each trial will have some studies repeated, some missing. From the 10^4 weighted means, the lowest and highest 16 percent were discarded, leaving the central 68-percent confidence region. This region has a central value and extent of $\beta = 2.7 \pm 0.7$. This is a conservative but robust estimate of the average value for β. As described above, all measurements have been corrected to a world model with $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$.

If all results are transformed to an Einstein-de Sitter Universe with $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$, the bootstrap-resampling 68-percent confidence interval is $\beta = 3.3 \pm 0.8$.

4. Discussion

Despite the scatter in Figure 1, the decline in comoving star-formation rate density $\dot{\rho}_*$ from redshift unity to the present day is well confirmed by multiple studies. The best average value of the evolution exponent β, in the parameterization $\dot{\rho}_* \propto (1+z)^\beta$, is $\beta = 2.7 \pm 0.7$. This value is only four standard deviations from zero, but the confidence interval is computed in the most conservative way (resampling); the straightforward weighted mean of the measurements gives a ten-sigma result.

In addition, almost all faint-galaxy studies which are relevant, but for one reason or another could not be included in this meta-analysis, bolster the conclusion that the star-formation rate has been dropping since redshift unity. Faint galaxies are bluer than nearby galaxies (eg, Koo & Kron 1992; Smail et al. 1995; Williams et al. 1996). The surface brightnesses, colors, and line emission of normal galaxy disks appear to have all been dropping (Schade et al. 1996; Lilly et al. 1998);

the same appears true for blue compact galaxies (Guzman et al. 1997). The luminosity functions of blue galaxies and star-forming galaxies have been evolving (Lilly et al. 1995; Heyl et al. 1997; Cram 1998; Mallén-Ornelas et al. 1999; Lin et al. 1999). Models of mid-infrared and sub-millimeter source counts may require a drop in star-formation activity since redshift unity (Blain et al. 1999; Elbaz et al. 1999). It is difficult to understand the observed chemical evolution of damped Lyα absorbers without much higher star formation activity at redshift unity than the present day (Pei & Fall 1995; Pei et al. 1999). Perhaps more indirect, the fraction of galaxies classified as "irregular" appears to be dropping with cosmic time (eg, Griffiths et al. 1994; Abraham et al. 1996; Odewahn et al. 1996; van den Bergh et al. 2000), and irregulars, locally, have above-average star-formation rates.

The mere consistency of these star-formation studies is only half the story. It is equally important that the studies span a wide range of observational techniques, and a range of physically different star-formation indicators. This heterogeneity makes their consistency much more impressive and much more convincing. In particular the different methods have different sensitivities to dust extinction and the slope of the initial mass function of stars; it is hard to argue that the observed trends are conspiracies of dust and mass function variability.

The evolution in star-formation rates is the most secure result in the field of galaxy evolution.

Incidentally, this also makes it the strongest argument from galaxy evolution against the pure steady-state model of cosmic origins (Bondi & Gold 1948; Hoyle 1948).

If the best-fit value of β and its conservatively estimated uncertainty are taken at face value, then $\beta > 1.3$ in the $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$ world model and $\beta > 1.5$ in the $(\Omega_M, \Omega_\Lambda) = (1.0, 0.0)$ world model. In either case, this implies that not only has the comoving star formation rate density $\dot{\rho}_*(z)$ been declining since redshift unity, but so has $t(z)\,\dot{\rho}_*(z)$, the comoving star formation density per logarithmic interval in cosmic time. This function $t(z)\,\dot{\rho}_*(z)$ more accurately represents the formation time of the bulk of stars. Because β is above the logarithmically divergent value ($\beta > 1.3$ in the default world model), most of the stellar mass at the present day ought to be in old (> 6 Gyr) stellar populations. This is the primary "prediction" of this meta-analysis; it appears to be consistent with the data (Fukugita et al. 1998; Hogg et al. 2002).

In addition to observations of distant galaxies, we have another powerful and independent "fossil record" of galaxy formation and evolution: Our own Galaxy contains stellar populations formed over the entire history of the Universe. The star formation history of the Galaxy can be inferred from its internal distribution of apparent stellar ages. Unfortunately, the distribution measured in the Solar neighborhood is not consistent with a large decline in the Galaxy's star formation rate over the last ~ 8 Gyr (Barry 1988; Pardi & Ferrini 1994; Prantzos & Silk 1998; Rocha-Pinto et al. 2000; Gizis et al. 2002). Is the Milky Way atypical? Or, perhaps more likely, it may be that measurements of the age distribution in the solar neighborhood not representative of the Galaxy as a whole; this is likely if a galaxy's stars are formed from the inside out. The resolution of this inconsistency between high-redshift and Milky-Way determinations of the star-

formation rate may lead to great progress in cosmology and galaxy evolution.

It is a pleasure to thank Mike Blanton, Karl Glazebrook, Deborah Haarsma, Heath Jones, Jim Peebles, David Schlegel, Rosemary Wyse and Sara Zimmerman for help with the literature, scientific discussions, and software. This research made use of the NASA ADS Abstract Service.

REFERENCES

Abraham, R. G., Tanvir, N. R., Santiago, B. X., Ellis, R. S., Glazebrook, K., & van den Bergh, S. 1996, MNRAS, 279, L47

Barry, D. C. 1988, ApJ, 334, 436

Bell, E. F. & Kennicutt, R. C. 2001, ApJ, 548, 681

Blain, A. W., Smail, I., Ivison, R. J., & Kneib, J.-P. 1999, MNRAS, 302, 632

Bondi, H. & Gold, T. 1948, MNRAS, 108, 252

Brinchmann, J. & Ellis, R. S. 2000, ApJ, 536, L77

Bruzual A., G. & Charlot, S. 1993, ApJ, 405, 538

Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582

Carlberg, R. G., Cowie, L. L., Songaila, A., & Hu, E. M. 1997, ApJ, 484, 538

Carlberg, R. G., Yee, H. K. C., Morris, S. L., Lin, H., Hall, P. B., Patton, D., Sawicki, M., & Shepherd, C. W. 2000, ApJ, 542, 57

Cohen, J. G. 2002, ApJ, 567, 672

Condon, J. J. 1992, ARA&A, 30, 575

Connolly, A. J., Szalay, A. S., Dickinson, M., Subbarao, M. U., & Brunner, R. J. 1997, ApJ, 486, L11

Cowie, L. L., Hu, E. M., Songaila, A., & Egami, E. 1997, ApJ, 481, L9

Cowie, L. L., Songaila, A., & Barger, A. J. 1999, ApJ, 118, 603

Cram, L. E. 1998, ApJ, 506, L85

Elbaz, D. et al. 1999, A&A, 351, L37

Filippenko, A. V. 1997, ARA&A, 35, 309

Flores, H., Hammer, F., Thuan, T. X., Césarsky, C., Desert, F. X., Omont, A., Lilly, S. J., Eales, S., Crampton, D., & Le Fèvre, O. 1999, ApJ, 517, 148

Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

Gallego, J., Zamorano, J., Arágon-Salamanca, A., & Regg, M. 1995, ApJ, 455, L1

Ghosh, P. & White, N. E. 2001, ApJ, 559, L97

Gizis, J. E., Reid, I. N., & Hawley, S. L. 2002, AJ, 123, 3356

Glazebrook, K., Blake, C., Economou, F., Lilly, S., & Colless, M. 1999, MNRAS, 306, 843

Griffiths, R. E. et al. 1994, ApJ, 435, L19

Guzman, R., Gallego, J., Koo, D. C., Phillips, A. C., Lowenthal, J. D., Faber, S. M., Illingworth, G. D., & Vogt, N. P. 1997, ApJ, 489, 559

Haarsma, D. B., Partridge, R. B., Windhorst, R. A., & Richards, E. A. 2000, ApJ, 544, 641

Hammer, F., Flores, H., Lilly, S. J., Crampton, D., Le Fevre, O., Rola, C., Mallen-Ornelas, G., Schade, D., & Tresse, L. 1997, ApJ, 481, 49

Heyl, J., Colless, M., Ellis, R. S., & Broadhurst, T. 1997, MNRAS, 285, 613

Hogg, D. W. 1998, PhD thesis, California Institute of Technology

—. 1999, astro-ph/9905116

Hogg, D. W., Blanton, M. R., Strateva, I., Bahcall, N. A., Brinkmann, J., Csabai, I., Doi, M., Fukugita, M., Hennessy, G., Ivezić, Z., Knapp, G. R., Lamb, D. Q., Lupton, R., Munn, J. A., Nichol, R., Schlegel, D. J., Schneider, D. P., & York, D. G. 2002, AJ, 124, 646

Hogg, D. W., Cohen, J. G., & Blandford, R. 2000, ApJ, 545, 32

Hogg, D. W., Cohen, J. G., Blandford, R., & Pahre, M. A. 1998, ApJ, 504, 622

Hopkins, A. M., Connolly, A. J., Haarsma, D. B., & Cram, L. E. 2001, astro-ph, 0103253

Hoyle, F. 1948, MNRAS, 108, 372

Jones, D. H. & Bland-Hawthorn, J. 2001, ApJ, 550, 593

Kennicutt, R. C. 1992, ApJ, 388, 310

Koo, D. C. & Kron, R. G. 1992, ARA&A, 30, 613

Kudritzki, R. & Puls, J. 2000, ARA&A, 38, 613

Lanzetta, K. M., Yahata, N., Pascarelle, S., Chen, H.-W., & Fernández-Soto, A. 2002, ApJ, 570, 492

Le Févre, O., Hudon, D., Lilly, S. J., Crampton, D., Hammer, F., & Tresse, L. 1996, ApJ, 461, 534

Leitherer, C. & Heckman, T. M. 1995, ApJS, 96, 9

Li, A. & Draine, B. T. 2002, ApJ, 572, 232

Lilly, S. et al. 1998, ApJ, 500, 75

Lilly, S. J., Le Fèvre, O., Crampton, D., Hammer, F., & Tresse, L. 1995, ApJ, 455, 50

Lilly, S. J., Le Fevre, O., Hammer, F., & Crampton, D. 1996, ApJ, 460, L1

Lin, H., Yee, H. K. C., Carlberg, R. G., Morris, S. L., Sawicki, M., Patton, D. R., Wirth, G., & Shepherd, C. W. 1999, ApJ, 518, 533

Madau, P., Pozzetti, L., & Dickinson, M. 1998, ApJ, 498, 106

Mallén-Ornelas, G., Lilly, S. J., Crampton, D., & Schade, D. 1999, ApJ, 518, L83

Martin, C., Friedman, P., Schiminovich, D., Madore, B., Bianchi, L., Szalay, A., Heckman, T., Milliard, B., Malina, R., Siegmund, O., Welsh, B., & Rich, M. 1997, BAAS, 29, 1309

Mobasher, B., Cram, L., Georgakakis, A., & Hopkins, A. 1999, MNRAS, 308, 45

Odewahn, S. C., Windhorst, R. A., Driver, S. P., & Keel, W. C. 1996, ApJ, 472, L13

Pardi, M. C. & Ferrini, F. 1994, ApJ, 421, 491

Pei, Y. C. & Fall, S. M. 1995, ApJ, 454, 69

Pei, Y. C., Fall, S. M., & Hauser, M. G. 1999, ApJ, 522, 604

Prantzos, N. & Silk, J. 1998, ApJ, 507, 229

Rocha-Pinto, H. J., Scalo, J., Maciel, W. J., & Flynn, C. 2000, A&A, 358, 869

Rowan-Robinson, M. et al. 1997, MNRAS, 289, 490

Sanders, D. B. & Mirabel, I. F. 1996, ARA&A, 34, 749

Schade, D., Carlberg, R. G., Yee, H. K. C., Lopez-Cruz, O., & Ellingson, E. 1996, ApJ, 465, L103

Smail, I., Hogg, D. W., Yan, L., & Cohen, J. G. 1995, ApJ, 449, L105

Small, T. A., Ma, C., Sargent, W. L. W., & Hamilton, D. 1999, ApJ, 524, 31

Sullivan, M., Mobasher, B., Chan, B., Cram, L., Ellis, R., Treyer, M., & Hopkins, A. 2001, ApJ, 558, 72

Sullivan, M., Treyer, M. A., Ellis, R. S., Bridges, T. J., Milliard, B., & Donas, J. . 2000, MNRAS, 312, 442

Thompson, R. I., Weymann, R. J., & Storrie-Lombardi, L. J. 2001, ApJ, 546, 694

Tresse, L. & Maddox, S. J. 1998, ApJ, 495, 691

Treu, T., Stiavelli, M., Casertano, S., Møller, P., & Bertin, G. 1999, MNRAS, 308, 1037

Treyer, M. A., Ellis, R. S., Milliard, B., Donas, J., & Bridges, T. J. 1998, MNRAS, 300, 303

van den Bergh, S., Cohen, J. G., Hogg, D. W., & Blandford, R. 2000, AJ, 120, 2190

Vogt, N. P., Forbes, D. A., Phillips, A. C., Gronwall, C., Faber, S. M., Illingworth, G. D., & Koo, D. C. 1996, ApJ, 465, L15

Vogt, N. P., Phillips, A. C., Faber, S. M., Gallego, J., Gronwall, C., Guzman, R., Illingworth, G. D., Koo, D. C., & Lowenthal, J. D. 1997, ApJ, 479, L121

Williams, R. E. et al. 1996, AJ, 112, 1335

Yan, L., McCarthy, P. J., Freudling, W., Teplitz, H. I., Malumuth, E. M., Weymann, R. J., & Malkan, M. A. 1999, ApJ, 519, L47

This preprint was prepared with the AAS LaTeX macros v5.0.

Table 1. star-formation rate measurements, corrected

reference technique $(h, \Omega_M, \Omega_\Lambda)$ [a]	z [b]	$\log_{10} \dot{\rho}_*$ [c]	β [d]
Lilly et al. (1996) [e]	0.35	-2.015 ± 0.075	3.93 ± 1.07
rest-frame ultraviolet	0.60	-1.742 ± 0.075	
$(0.50, 1.00, 0.00)$	0.85	-1.457 ± 0.150	
Hammer et al. (1997)	0.48	-1.797 ± 0.055	7.22 ± 1.03
spectral features, esp. [O II]	0.62	-1.358 ± 0.028	
$(0.50, 1.00, 0.00)$	0.85	-1.175 ± 0.087	
Rowan-Robinson et al. (1997)	0.55	-0.815 ± 0.145	6.93 ± 4.16
far infrared (inferred)	0.85	-0.282 ± 0.285	
$(0.50, 1.00, 0.00)$			
Hogg et al. (1998)	0.20	-1.827 ± 0.133	2.88 ± 0.61
[O II] line emission	0.40	-1.227 ± 0.093	
$(1.00, 0.30, 0.00)$	0.60	-1.141 ± 0.067	
	0.80	-1.200 ± 0.078	
	1.00	-0.899 ± 0.097	
Cowie et al. (1999) [f]	0.37	-1.890 ± 0.122	1.09 ± 1.35
rest-frame ultraviolet	0.63	-1.666 ± 0.119	
$(0.65, 1.00, 0.00)$	0.78	-1.773 ± 0.094	
Flores et al. (1999)	0.35	-1.445 ± 0.275	4.47 ± 3.02
far infrared (inferred)	0.60	-1.167 ± 0.250	
$(0.50, 1.00, 0.00)$	0.80	-0.882 ± 0.260	
Mobasher et al. (1999) [g]	0.15	-1.553 ± 0.080	-4.05 ± 1.18
1.4 GHz radio	0.50	-2.021 ± 0.110	
$(0.50, 1.00, 0.00)$			
Haarsma et al. (2000)	0.28	-1.157 ± 0.173	3.61 ± 1.48
1.4 GHz radio	0.46	-0.920 ± 0.171	
$(0.50, 1.00, 0.00)$	0.60	-0.869 ± 0.209	
	0.81	-0.598 ± 0.151	
Jones & Bland-Hawthorn (2001) [h]	0.08	-1.892 ± 0.301	2.21 ± 2.76
Hα line emission	0.24	-1.499 ± 0.092	
$(0.50, 1.00, 0.00)$	0.40	-1.501 ± 0.166	
Lanzetta et al. (2002) [i]	0.25	-2.061 ± 0.065	0.67 ± 0.68
rest-frame ultraviolet	0.75	-1.963 ± 0.075	
$(1.00, 1.00, 0.00)$			

Table 1—Continued

reference technique $(h, \Omega_M, \Omega_\Lambda)$ [a]	z [b]	$\log_{10} \dot{\rho}_*$ [c]	β [d]
combined Hα [j]	0.03	-1.907 ± 0.040	3.75 ± 0.51
Hα line emission	0.20	-1.620 ± 0.040	
$(0.50, 1.00, 0.00)$	0.90	-0.967 ± 0.145	
weighted mean			2.74 ± 0.28
bootstrap resampling [k]			2.68 ± 0.75

[a]Cosmological parameters used in the original reference. For the purposes of fitting, the results have been corrected to an effective world model of $(h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7)$; see the text for details.

[b]z is redshift. Only points at redshifts $z \leq 1$ were included in the fits.

[c]$\dot{\rho}_*$ is the comoving star-formation rate density. All measurements have been corrected to the fiducial world model as described in the text.

[d]β is the exponent in parameterization $\dot{\rho}_* \propto (1+z)^\beta$. See text for explanation of the fitting technique and calculation of uncertainties.

[e]Data for Lilly et al. (1996) are taken from analysis of Glazebrook et al. (1999).

[f]Luminosity density in Cowie et al. (1999) has been converted to star-formation rate with the conversion of Cowie et al. (1997).

[g]Mobasher et al. (1999) do not give values for the cosmological parameters; I have *guessed* (0.5,1.0,0.0).

[h]Integrations of the functions in Jones & Bland-Hawthorn (2001) were kindly provided by Jones (private communication).

[i]The "scaled break intensity" results of Lanzetta et al. (2002) are used here.

[j]The "combined Hα" line is a compilation of three similar studies by Gallego et al. (1995), Tresse & Maddox (1998), and Glazebrook et al. (1999), with star-formation analysis by Glazebrook et al. (1999).

[k]The central value and uncertainty reported for the bootstrap resampling indicate the central 68-percent confidence interval; see the text for details.

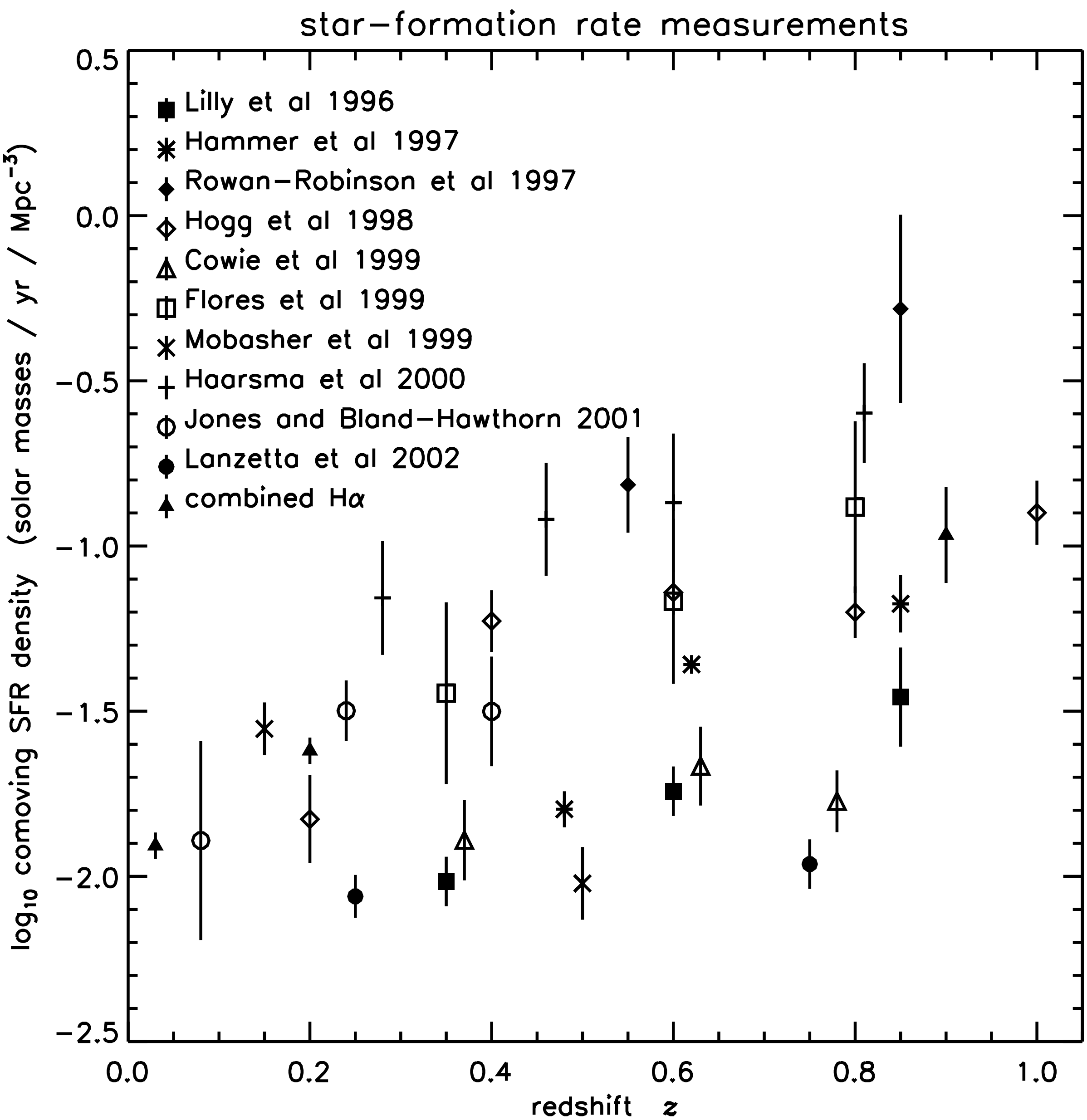

Fig. 1.— The star-formation rate measurements used in the meta-analysis, all corrected (crudely; see text) to a world model of $(h, \Omega_M, \Omega_\Lambda) = (0.7, 0.3, 0.7)$. See the text and Table 1 for details.

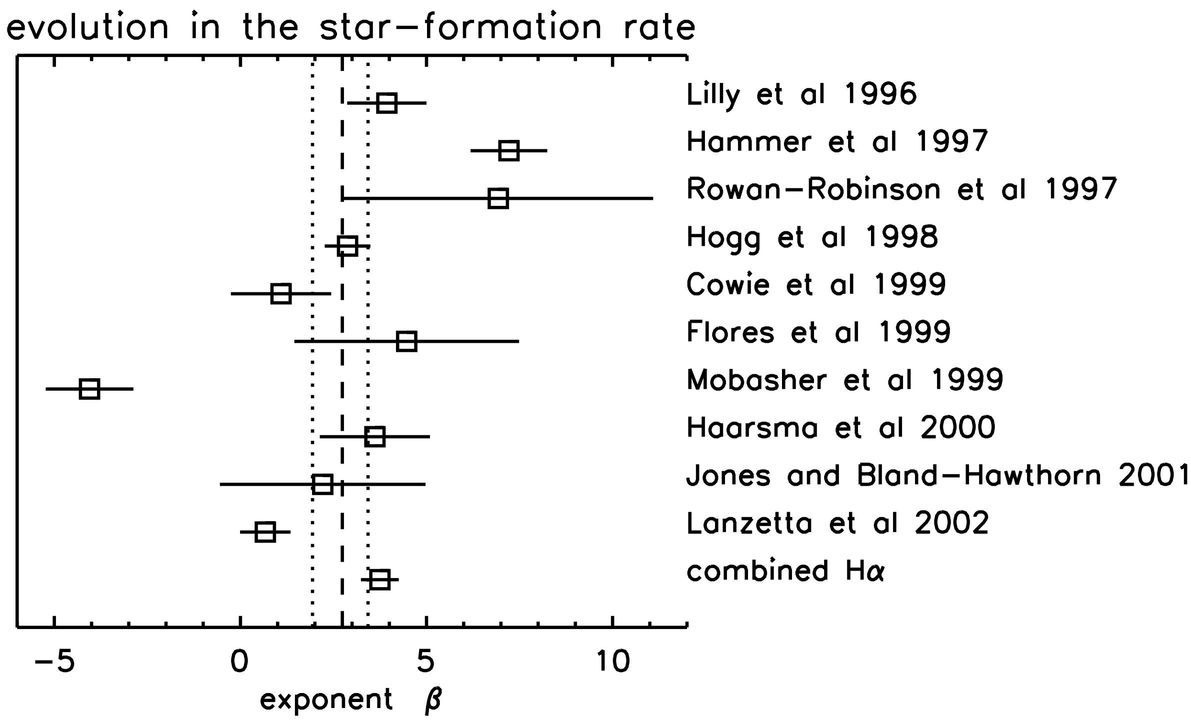

Fig. 2.— The best-fit values of evolutionary exponent β in the parameterization $\dot{\rho}_* \propto (1+z)^\beta$ for the measurements in Table 1 and Figure 1, with world model $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$. The fits are performed under a number of assumptions described in the text. The dashed line is the weighted mean and the dotted lines indicate the central 68-percent confidence interval from the bootstrap resampling described in the text.